Nuclear Reactions with light ion and photon beams; Contributions to Neutrino Astrophysics

1. Incompressibility and Giant Resonances
   (ISGMR, ISGDR)
2. Charge exchange reactions
3. Photon Beams for \((\gamma,\gamma'), (\gamma,n)\)

M. Fujiwara: NNR05 Dec.2 – 4, 2005 CAST/SPring-8, Japan
In the supernova explosion processes, the iron core absorbs electrons via the electron capture process, and the core is dominated with neutron excess nuclei.

This process proceeds at $\bar{\bar{\Delta}}_0$

In the region $\bar{\bar{\Delta}}_0$, the core become hard

Rebounding happens

Explosion

Thus, an important factor for supernova explosion is the hardness of the core with neutron excess nuclei.

Incompressibility

Isotope dependence of Incompressibility

$K_{\text{sym}} \left( \frac{N-Z}{A} \right)^2$
Two Major Unsolved Issues in Nuclear Incompressibility

1. Different $K_A (K_\infty)$ values from ISGMR and ISGDR

$$E_{ISGMR} \doteq \sqrt[3]{\frac{K_A}{m\langle r^2 \rangle}}$$

$$E_{ISGDR} \doteq \sqrt[3]{\frac{7K_A + (27/25)\varepsilon_F}{m\langle r^2 \rangle}}$$

2. From the same GMR data, Non-relativistic and Relativistic calculations gave different $K_\infty$ values;

   220 MeV  non-rel.
   270 MeV  rel.

The first of these has been resolved. With the background-free spectra, ISGDR strength at higher Ex than before. Now, same calculations give reasonable agreement with $E_{GMR}$ and $E_{ISGDR}$.

The second issue still remained unsolved.
There was the consensus among the theorists that the Primary difference between the non-relativistic and relativistic calculations comes from the “symmetry energy” term.

\[ K_A \sim K_\infty (1+cA^{-1/3}) + K_{\text{sym}} ((N-Z)/A)^2 + K_{\text{Coul}} Z^2 A^{-4/3} \]

\[ K_{\text{sym}} = -400 \sim +466 \text{ MeV; not well obtained} \]

B.A. Li, PRL 85, 4221 (2000),
R.J. Furnstahl, nucl-th/0112085.

Clearly the (N-Z)/A term is very important in nuclear structure, heavy ion collision, astronuclearphysics.

The widest range of (N-Z)/A in an isotope series (in medium and heavy mass nuclei) is in Sn:

\[ ^{112}\text{Sn} \ \ 0.107 \]
\[ ^{124}\text{Sn} \ \ 0.194 \]
(\(\alpha,\alpha'\)) spectra at 386 MeV

Uchida et al., PRC
Giant Resonances

By M. Itoh for RCNP experiments

- (T=0)
  L=0 ISGMR
  L=1 ISGDR
  L=2 ISGQR
  L=3 ISGOR
  ... 
- (T=1)
  L=1 IVGDR

\[ \sum \]
Giant Resonance studies at RCNP, Texas, KVI....

By A. Krasznahorkay
Experimental data on ISGMR

ISGMR energy $E_{\text{ISGMR}}$

- $80A^{-1/3}$
- Sharma et al.
- Youngblood et al.
- Lui et al.
- Uchida et al.

Recent data

Recent data

Recent data

Mass number $A$

$E_{\text{ISGMR}}$ (MeV)
M. Fujiwara et al., NIM A 422 (1999) 484
Energy Spectra

ND, RCNP, KVI, Kyoto, Konan collaboration

- $^{124}\text{Sn}$
- $^{116}\text{Sn}$
- $^{112}\text{Sn}$
- $^{118}\text{Sn}$
- $^{114}\text{Sn}$
- $^{120}\text{Sn}$
Data Analysis

Background rejection with the focal plane detector system of the spectrometer Grand Raiden.

(a) one-dimensional spectrum along the vertical direction. Background events correspond to the hatched area. True and background events are in the central region.

(b) The energy spectra for the true + background events, and for the background Events.

(c) Difference spectrum for true events.
Multipole-decomposition analysis

\[ \sigma^{\text{exp}}(\theta, E_x) = \sum_{L} a_L(E_x) \sigma^{\text{calc}}_L(\theta, E_x) \]

Cross sections

DWBA calculations

(\(L=0\sim15\)) and IVGDR cross section
### Breit-Wigner function

\[
\sigma(E) = \frac{\sigma_m}{(E - E_m)^2 + \Gamma_m^2}
\]

<table>
<thead>
<tr>
<th></th>
<th>$E_m$ (MeV)</th>
<th>$\Gamma_m$ (MeV)</th>
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<tbody>
<tr>
<td>$^{112}$Sn</td>
<td>16.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$^{114}$Sn</td>
<td>16.0</td>
<td>0.1</td>
</tr>
<tr>
<td>$^{116}$Sn</td>
<td>15.8</td>
<td>0.1</td>
</tr>
<tr>
<td>$^{118}$Sn</td>
<td>15.7</td>
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</tr>
<tr>
<td>$^{120}$Sn</td>
<td>15.3</td>
<td>0.1</td>
</tr>
<tr>
<td>$^{122}$Sn</td>
<td>15.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$^{124}$Sn</td>
<td>14.9</td>
<td>0.1</td>
</tr>
</tbody>
</table>

$^{112,114,118,120,122,124}$Sn : this work

$^{116}$Sn : Uchida et al.
ISGMR energy $E_{\text{ISGMR}}$

![Graph showing ISGMR energy vs mass number $A$]
\[ K_A \sim K_\infty (1 + c A^{-1/3}) + K_{\text{sym}} ((N - Z)/A)^2 + K_{\text{Coul}} Z^2 A^{-4/3} \]

\[ c = -1 \quad K_{\text{Coul}} = -5 \]

\[-580 < K_{\text{sym}} < -380\]

\[ E_{\text{ISGMR}} = \hbar \sqrt{\frac{K_A}{m < r^2 >}} \]

G. Colo et al. PRC 70 024307 (2004)
Effects of the in-medium nucleon-nucleon cross sections

-550 < $K_{asy}$ < -450 MeV close to that extracted from Osaka giant resonance data

0.7 < $\gamma$ < 1.1 in fitting $E_{sym} = 32(\frac{\sigma}{\sigma_0})^\gamma$

Bao-An Li et al., ND workshop
July 14-15, 2005; Bao-An Li and L.-W. Chen nucl-th/0508024
Calculated by Jorge Piekarewicz
Baumer et al.,

KVI

(d,²He), (t,³He), (⁷Li,⁷Be)
SN explosion, nuclear synthesis, ...

Z-1 \( A_{N+1} \)

Z+1 \( A_{N-1} \)

(z, A_N)

(p,n), (³He,t)
Solar neutrino detection, double beta decay, ...

Fujiiwqara et al.,

RCNP

(e,e'), (γ,γ'), (p,p'), (α,α')
Supernova, ...
~20 events were confirmed at Kamiokande and IMB
First (and only so far) neutrino detection from outside of the solar system
Because of water Čerenkov method, almost all the neutrinos were $\nu_e$: $\nu_e + p \rightarrow n + e^+$

About 50 kpc distance from the earth
Neutrinos were detected about 2 hrs later than the optical observation.
Neutrino Flavors and Energy Distributions

- **Cross Section:** Coupling constant of weak interaction \( \sigma \approx 10^{-42} \text{ cm}^2 \)
  - \( \sim 10^{15} \) Smaller than cross sections in ordinary nuclear reaction
  - More neutrons than protons at core \( \leftrightarrow \begin{align*}
\bar{\nu}_e + n & \rightarrow p + e^- \\
\nu_e + p & \rightarrow n + e^+
\end{align*} \)
  - CC reactions (n\(\leftrightarrow\)p exchange) easily happen.

- **The radii of ‘Neutrino sphere’ are different in flavors.**

- **Prediction of neutrino energy distribution**
  
  \[
  \langle E(\nu_e) \rangle = 11 \text{ MeV} \\
  \langle E(\bar{\nu}_e) \rangle = 16 \text{ MeV} \\
  \langle E(\nu_x) \rangle = 25 \text{ MeV}
  \]

  Average energies depend on supernovae explosion model.

  **The first purpose is to measure energy distributions.**

  → **Equation of neutrino state and transmissivity can be known.**

  
Neutrino Detection via $^{208}$Pb

CC & NC reaction can be detected using nuclei with a low neutron decay threshold. Cross section is relatively higher.

Available to measure $\nu_\mu$ & $\nu_\tau$
Playing as 'Flavor Filter'.

- Neutral Current (NC) reaction
  \[
  \nu_i + ^{208}\text{Pb} \rightarrow \nu'_i + ^{208}\text{Pb} \quad or \\
  \nu_e + p \rightarrow \nu'_e + p'
  \]

- Charged-Current (CC) reaction
  \[
  \nu_e + ^{208}\text{Pb} \rightarrow e^- + ^{208}\text{Bi} \quad or \\
  \overline{\nu}_e + p \rightarrow e^+ + n
  \]

- 1-2 neutron decay from excited nuclei become neutrino signal.
Excitation Energy Spectra

A) Singles measurement
B) Neutron coincidence
C) $\gamma$-ray coincidence
D) Decay neutron ratio
E) Decay $\gamma$-ray ratio

(Scattering angle $0^\circ < \theta < 2^\circ$)

$^{208}\text{Pb}(^{3}\text{He},t)$
Statistical Decay and Model Calculation

- Direct Decay
- Statistical Decay

Comparison of statistical-model calculation and measurement

![Graph showing neutron multiplicity with no detection threshold]
• Energy distribution is compatible with statistical-model calculation.
• As fitting by using Maxwell-Boltzmann distribution function for neutron evaporation from a nuclei, 
  \[ f(E) \sim E \exp(-aE) \]
  the center energy became 1.0 ± 0.1 MeV.
Kawase et al.,

1. Direct counting of NRF yields
2. Both E1 and M1 excitations are used.
3. Self-corrections for experimental error
4. Circular polarized beam with high stability and high emittance is needed.

\[\gamma = 2 (T(E_1) - T(M1))\]

In the case of \(^{19}\text{F}\)

\[A_{\gamma} = 2 \frac{\langle \phi J^- | H_{\text{pnc}} | \phi J^+ \rangle}{E_+ - E_-} \]

\[A_{RL} = \frac{2}{\Delta E} \left\langle \frac{1}{2}^- | H_{\text{pnc}} | \frac{1}{2}^+ \right\rangle \left( \frac{\langle 1/2^+ | \mu | 1/2^+ \rangle - \langle 1/2^- | \mu | 1/2^- \rangle}{\langle 1/2^+ | O(E1) | 1/2^- \rangle} \right) (1 + \cos \theta)\]

109.9 keV
NRF \(\gamma\)-ray peak

1 eV

109.9 keV

\[\gamma_{\text{NRF}}\]

10 - 300

10 - 300

10 - 100 keV
Facility for Inverse Compton γ-ray beam at New-Subaru at SPring-8

1.5 GeV
TOP up operation
1-30 MeV photons
10^7 photons/sec.

Application:
Astrophysics,
Nuclear Physics

Straight line for Inverse Compton scattering
Nucleosynthesis by high energy photons

Heavy elements have been produced by stars in the Galaxy.

Massive stars have contaminations of heavy elements synthesized at early generation stars.

New isotopes are produced by photons in supernova explosions.

Temperature: $3 \times 10^9$ K!
Summary

1) ISGMR in $^{112,114,116,118,120,122,124}$Sn via $(\alpha,\alpha')$. We obtained the ISGMR cross section distribution and peak positions. $K_{\text{sym}}$ is most likely $-580 < K_{\text{sym}} < -380$ MeV.

2) Selected results from $(^3\text{He},t)$. $(d,^3\text{He})$, $(t,^3\text{He})$ results are shown.

3) Charge exchange reaction for supernova neutrino detector

4) $\gamma$-ray beam facility at SPring-8.
April 2005

Kawase et al.,
Density-dependent N- □ interaction

\[ V(|\vec{r} - \vec{r}'|, \rho_0(r')) = -V(1 + \beta_v \rho_0(r')^{2/3}) \exp(-|r - r'|^2 / \alpha_v) - iW(1 + \beta_w \rho_0(r')^{2/3}) \exp(-|r - r'|^2 / \alpha_w) \]

Interaction parameters were obtained for $^{124}$Sn by fitting the elastic scattering.

The angular distributions were calculated with the DWBA code “ECIS95”

<table>
<thead>
<tr>
<th>$^{124}$Sn</th>
<th>V(M □ V)</th>
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<tbody>
<tr>
<td>$^{124}$Sn</td>
<td>□ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □</td>
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</table>
$^{112}\text{Sn} \ 2^+ \ (1.257\text{MeV})$

$^{112}\text{Sn} \ 3^- \ (2.360\text{MeV})$
\( ^{120}\text{Sn} \) \( 2^+ \) (1.171 MeV)

\( ^{120}\text{Sn} \) \( 3^- \) (2.399 MeV)
\[ {^{124}}\text{Sn} \; 2^+ \; (1.131\text{MeV}) \]

\[ {^{124}}\text{Sn} \; 3^- \; (2.614\text{MeV}) \]

\[ {^{124}}\text{Sn} \; 4^+ \; (3.158\text{MeV}) \]